



# **KEA-144: Final Results of the Ground Operations Demonstration Unit for Liquid Hydrogen (GODU-LH2) Project**

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- LH<sub>2</sub> Operations Background
- Zero Boil-Odd and Densification History
- Integrated Refrigeration and Storage Concept
- Ground Operations Demonstration Unit for Liquid Hydrogen Project
  - Objectives
  - System Description
- GODU-LH2 Test Results
- Conclusions
- Questions

# Background



- In the 1950's and 1960's USAF and NASA requirements drove the development of large scale  $\text{LH}_2$  systems
- Kennedy Space Center has not substantially changed its  $\text{LH}_2$  hardware or processes since that time
- Inefficiencies lead to the loss of almost 50% of hydrogen purchased by SSC and KSC during the shuttle program
- Total Shuttle losses at KSC were calculated to be 24.6 M lbs of  $\text{LH}_2$ , or \$59M based on 2016 prices
- Re-liquefiers have been proposed for LC-39 but never incorporated by KSC
- Some technology development work done with densified propellants but never incorporated by NASA



# Zero Boil-Off (ZBO) History



- Zero boil off refers to the ability to store cryogenics for indefinite periods with no losses
- ZBO can be accomplished with re-liquefiers (use stored fluid as working fluid) or close cycle cryocoolers
  - 1950's Industrial gas industry develops re-liquefiers for helium storage
  - 1962 National Bureau of Standards develops hydrogen re-liquefier
  - 1967 Air Products designs hydrogen re-liquefier for in-space use
  - 1977 Martin Marietta proposes to incorporate a re-liquefier for use at LC-39 for upcoming Shuttle Program
  - 1991 Energetics Inc proposes re-liquefier for LC-39 also capable of recovering tanker and chilldown losses
  - 1993 Hydrogen Consultants Inc develops prototype closed cycle Joule-Thomson cryocooler for LC-39 zero boil off (SBIR Phase II)
  - 1999-2002 Space simulated ZBO testing at MSFC with commercial cryocooler, mixing pump, and axial jets
  - 2000's Multiple trade studies and cryocooler development projects for in space ZBO
  - 2002-06 ZBO testing using IRAS at Florida Solar Energy center
  - 2004 ZBO testing at GRC using LN<sub>2</sub> and commercial cryocooler
  - 2012-14 ZBO testing at GRC using flight like cryocooler and broad area cooling



# Densification History



- $\text{LH}_2/\text{LOX}$  are the most energetic chemical propellants practical, but  $\text{LH}_2$  suffers from low density and volumetric heat capacity.
- Hydrogen densification can be used to increase the liquid density and heat capacity
- Densification can lead to a large increase in payload mass (15%)
- NASA/USAF has investigated use of densified  $\text{LOX}/\text{LH}_2$  since the 1960's
  - 1960's National Bureau of Standards quantifies densified and slush hydrogen thermodynamic properties
  - 1977 Martin Marietta report on SSTO using densified  $\text{LOX}$  and  $\text{LH}_2$
  - 1988- 94 NASP X30 Slush Hydrogen Technology Program - large scale production, transfer and in-tank thermodynamics
  - 1995- 97  $\text{LH}_2$  densification prototype system - 2 lb/sec rig tested at K-Site X33 RLV Precursor Demo
  - 1996 Hot fire ignition test of RL10B-2 engine with densified  $\text{LH}_2$  at Plum Brook B2
  - 1998 Demonstration of  $\text{DLH}_2$  loading, hold and thermal stratification in a composite flight weight dual-lobe tank
  - 1997- 2001 Design, build and test of large scale  $\text{LOX}$  &  $\text{LH}_2$  propellant densification units for X-33/RLV flight
  - 2000 STA Tank Loading Tests w/GRC 30 lb/sec  $\text{LOX}$  PDU at GRC S40
  - 2001  $\text{LN}_2$  Performance Demo Tests w/GRC 8 lb/sec  $\text{LH}_2$  PDU at GRC S40 (funding terminated before hydrogen testing)
  - 2001 Space shuttle performance enhancement study with propellant densification – 8 mo. multi-center effort
  - 2002-06  $\text{LH}_2$  densification to 15K using IRAS with Florida Solar Energy Center
  - 2002-03 2nd GEN RLV Program -- funded three densification technology demonstrators (PHPK, Sierra Lobo, and LM/Praxair)
  - 2008 Design, fabrication & integration of a Cryogenic Propellant System capable of conditioning  $\text{LCH}_4$  (GRC)
  - 2015 SpaceX using densified  $\text{LOX}$ , not to increase mass to LEO, but to enable reusability

# Integrated Refrigeration and Storage (IRAS)



- Interface a cryogenic refrigerator to a liquid hydrogen storage tank via an internal heat exchanger
- Remove energy directly from the liquid to control bulk fluid
- Enables Zero Boil Off, Densification, and Liquefaction
- NASA and DoE funded small scale LH<sub>2</sub> IRAS proof of concept demonstration from 2002-06
- Exploration Technology Development Program funded IRAS Heat Exchanger characterization tests in 2008-09 as part of Cryogenic Fluid Management (CFM) Project
- Plans for ETDP large scale Integrated Refrigeration and Storage demonstration cancelled in FY10



- HEOMD recognized the need and called for “Efficient ground-based systems for cryogenic fluid storage and transfer” in the 2012 AES PRG
- GODU-LH2 combined with Autonomous Command and Control development to submit the Integrated Ground Operations Demonstration Units (IGODU) proposal
- Proposal scored a 92 during evaluations and was described as a “Strong effort of actual hardware development and highly relevant tasks”

## Project Goal

“Demonstrate cost efficient cryogenic operations on a relevant scale that can be projected onto future Spaceport architecture”

## Primary Objectives

1. Demonstrate zero loss storage and transfer of  $\text{LH}_2$  at a large scale.
2. Demonstrate hydrogen densification in storage tank
3. Demonstrate in situ hydrogen liquefaction





# Site Build-Up



September 30<sup>th</sup>, 2012



# Site Build-Up



January 9<sup>th</sup>, 2013





# Site Build-Up



January 13<sup>th</sup>, 2014



November 2015



April 2014



January 2014

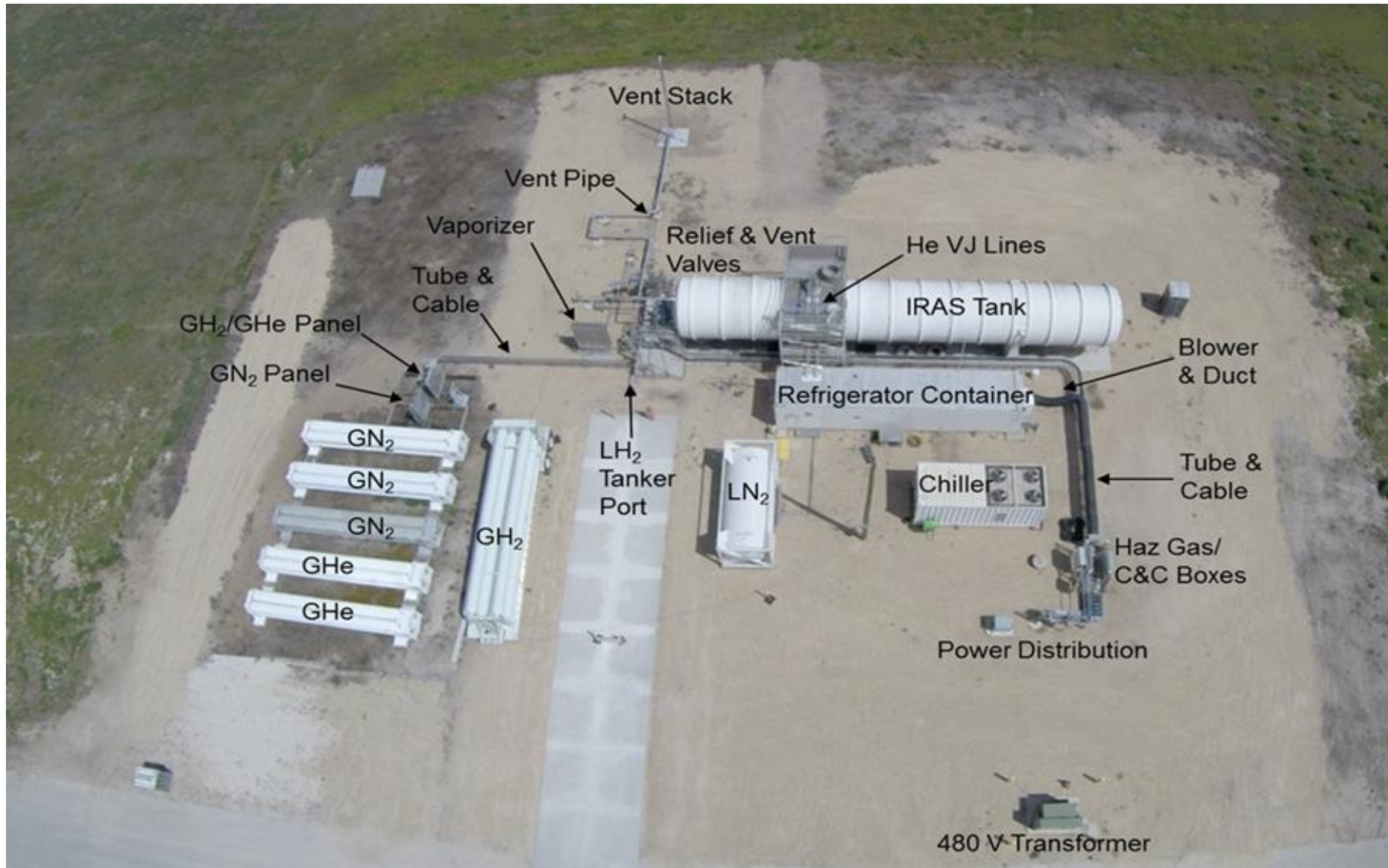


# GODU-LH2 Functional Diagram





# “Bird’s-eye View” of GODU-LH2 Site

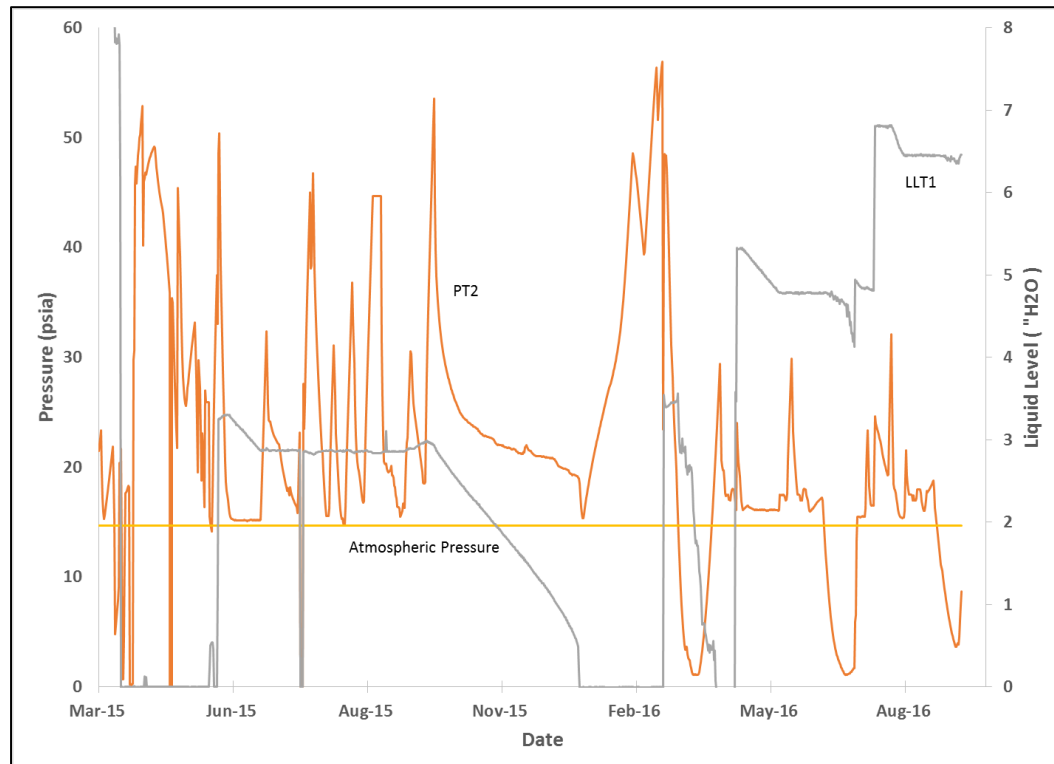


# Test Matrix and Timeline



- Completed Test Readiness Review on February 12, 2015
- First tanker offload occurred May 21, 2015
- Refrigerator contamination from October 2015 until March 2016
- Compressed testing from March 2016 until October 2016

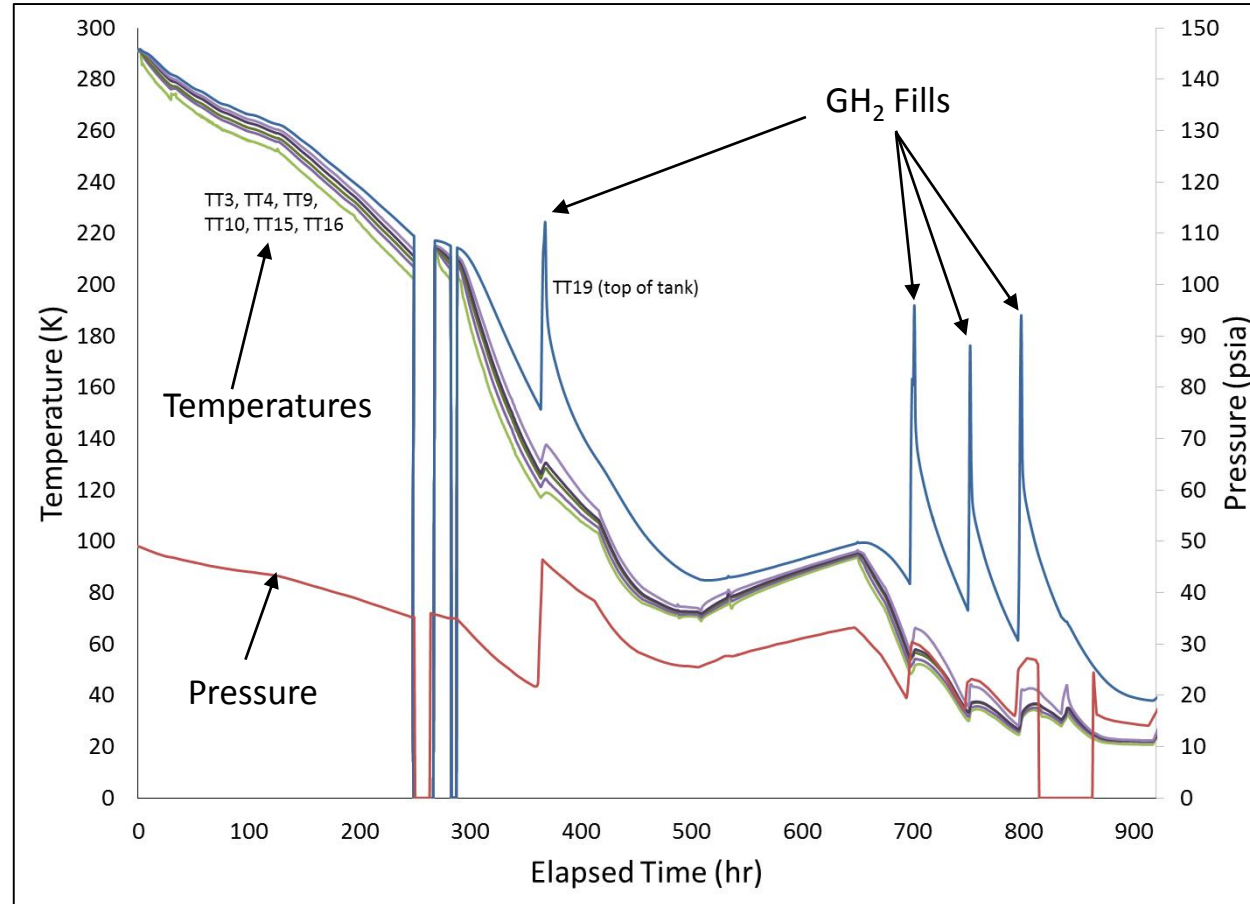
Test	Start Date	End Date
Chiltdown	4/9/2015	5/21/2015
Tanker 1 Offload	5/21/2015	5/29/2015
Tanker 2 Offload	5/3/2016	5/6/2016
Tanker 3 Offload	8/3/2016	8/12/2016
33% Boil Off	5/29/2015	6/19/2015
66% Boil Off	5/6/2016	5/31/2016
100% Boil Off	8/14/2016	8/24/2016
33% ZBO (Press Control)	4/25/2016	5/3/2016
66% ZBO (Press Control)	6/12/2016	6/21/2016
100% ZBO (Press Control)	8/25/2016	9/6/2016
33% ZBO (Temp Control)	6/23/2015	7/13/2015
66% ZBO (Temp Control)	6/21/2016	6/29/2016
100% ZBO (Temp Control)	9/6/2016	9/12/2016
33% ZBO (Duty Cycle)	8/4/2015	8/11/2015
66% ZBO (Duty Cycle)	6/5/2016	6/13/2016
100% ZBO (Duty Cycle)	8/12/2016	8/16/2016
33% Densification	3/24/2016	4/21/2016
66% Densification	6/29/2016	7/23/2016
100% Densification	9/12/2016	10/5/2016
0% Liquefaction	4/9/2015	5/21/2015
33% Liquefaction	9/23/2015	10/8/2015
66% Liquefaction	7/22/2016	8/2/2016



# Zero-Loss Tank Childdown Test Results



- Initial Conditions
  - 99.95% GH<sub>2</sub> at 300 K and 40 psia.
- Lock up tank and turn on refrigerator at T-0.
- Add GH<sub>2</sub> as tank pressure decreases
- Final Conditions
  - Tank near isothermal at 20.8K - 22.4 K and 14.7 psia
  - Saturated vapor with condensation on HX tubing
- Multiple lessons learned would decrease total timeline in the future



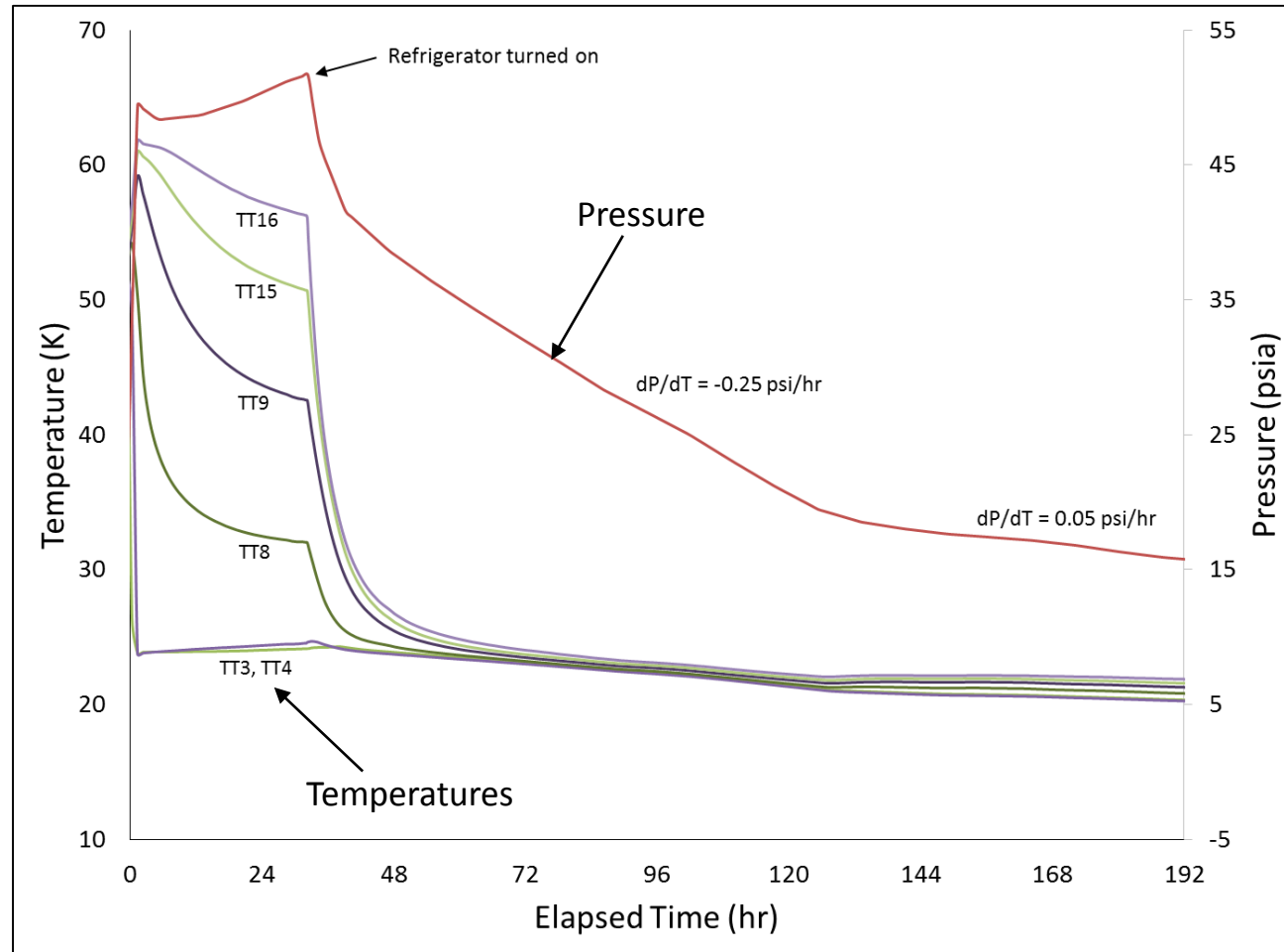
**Conclusion: IRAS enables zero-loss childdown of a large cryogenic vessel**



# Zero-Loss Tanker Offload Test Results



- Based on STS Program data, 13% of purchased  $\text{LH}_2$  is lost due to transport and offload inefficiency
- Heat from transport and line chilldown can be removed by refrigerator, allowing no loss offload
- Zero-loss tanker offloads were achieved at 33%, 67%, and 100% fill levels



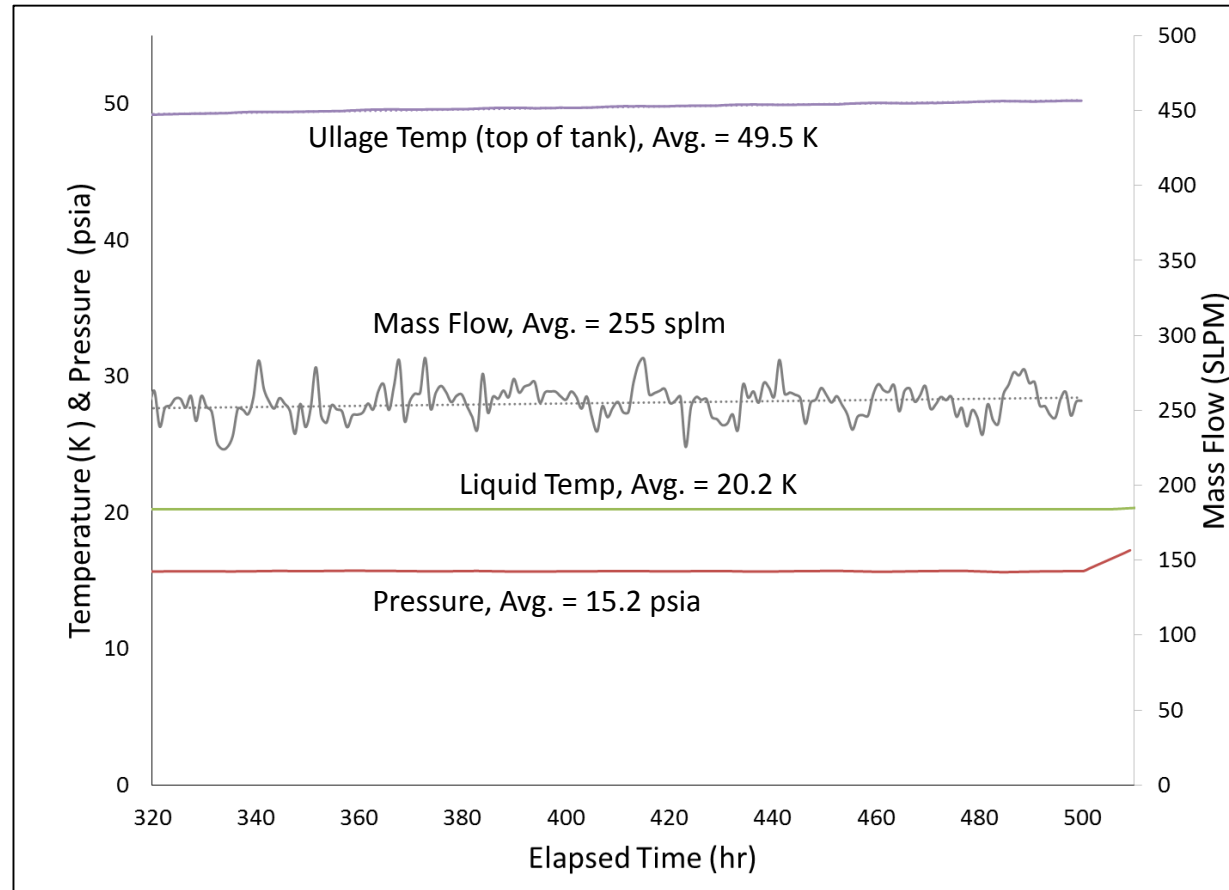
**Conclusion: IRAS enables zero-loss tanker offloads at all fill levels**

# Boil-off Heat Leak Test Results



- Boil off testing to quantify heat leak was conducted at 3 fill levels
- Vented thru control valve and mass flow meter
- Pre-test analysis estimated 300 W

**Conclusion: Tank heat leak was quantified at three fill levels and agreed closely with pretest estimates**



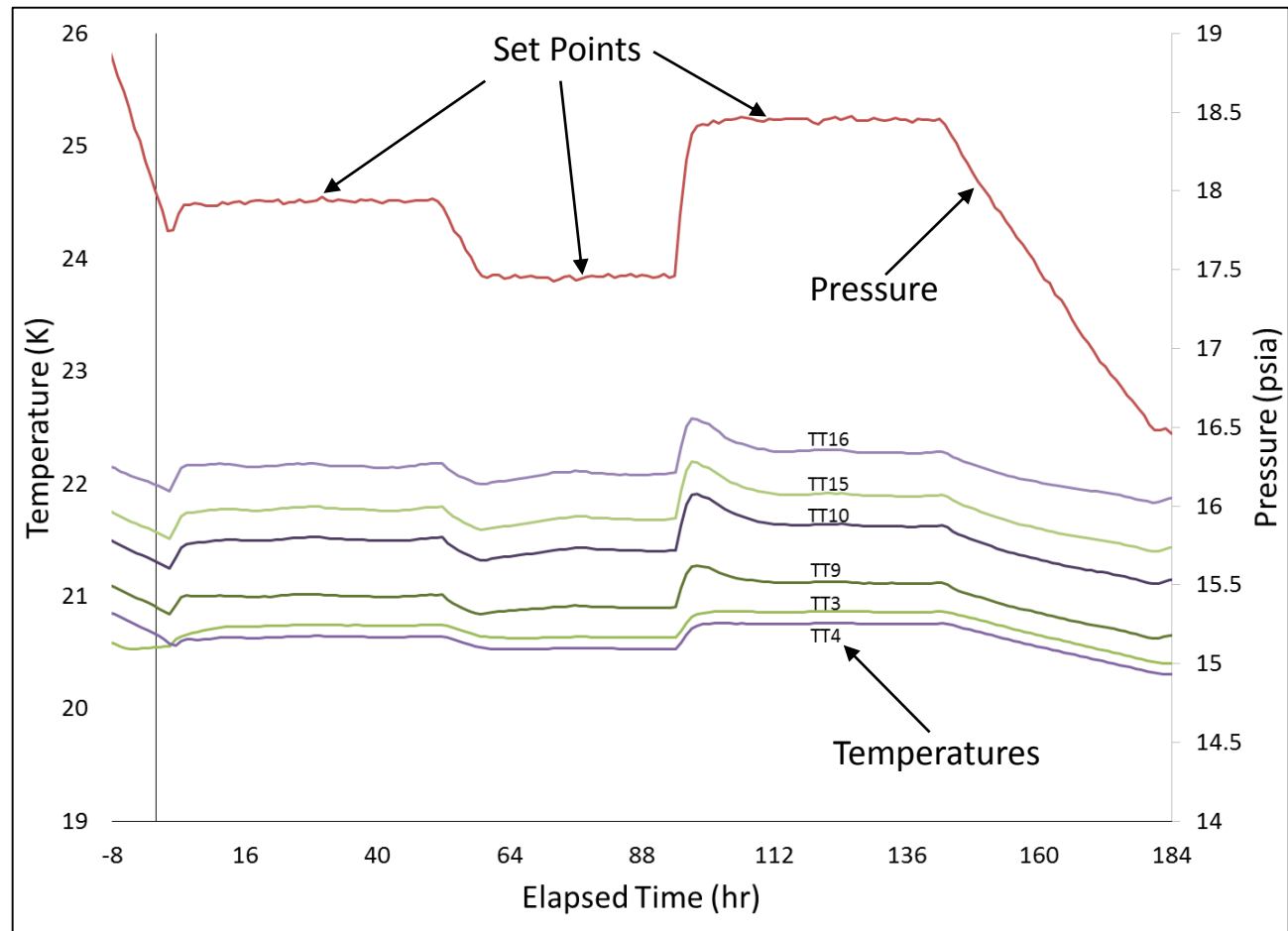
$$\dot{Q} = \dot{m} * \{h_{fg} + (h_{ullage} - h_{sat,vapor})\} \text{ [W]}$$

Level	MF3	PT2	TT19	Q <sub>L</sub>	Q <sub>V</sub>	Q
%	(slm)	(psia)	(K)	(W)	(W)	(W)
33	255	15.2	49.5	170	120	290
67	295	16.6	41.3	196	100	296
100	351	15.9	34.5	234	81	315

# ZBO Pressure Control Test Results



- GODU-LH2 software controlled refrigerator to achieve and maintain IRAS tank pressure set-point.
- No LN<sub>2</sub> pre-cooling used
- Approach set points from above and below
- Pressure stability +/- 0.5% for all three fill levels
- Near isothermal temperature profile following saturation line



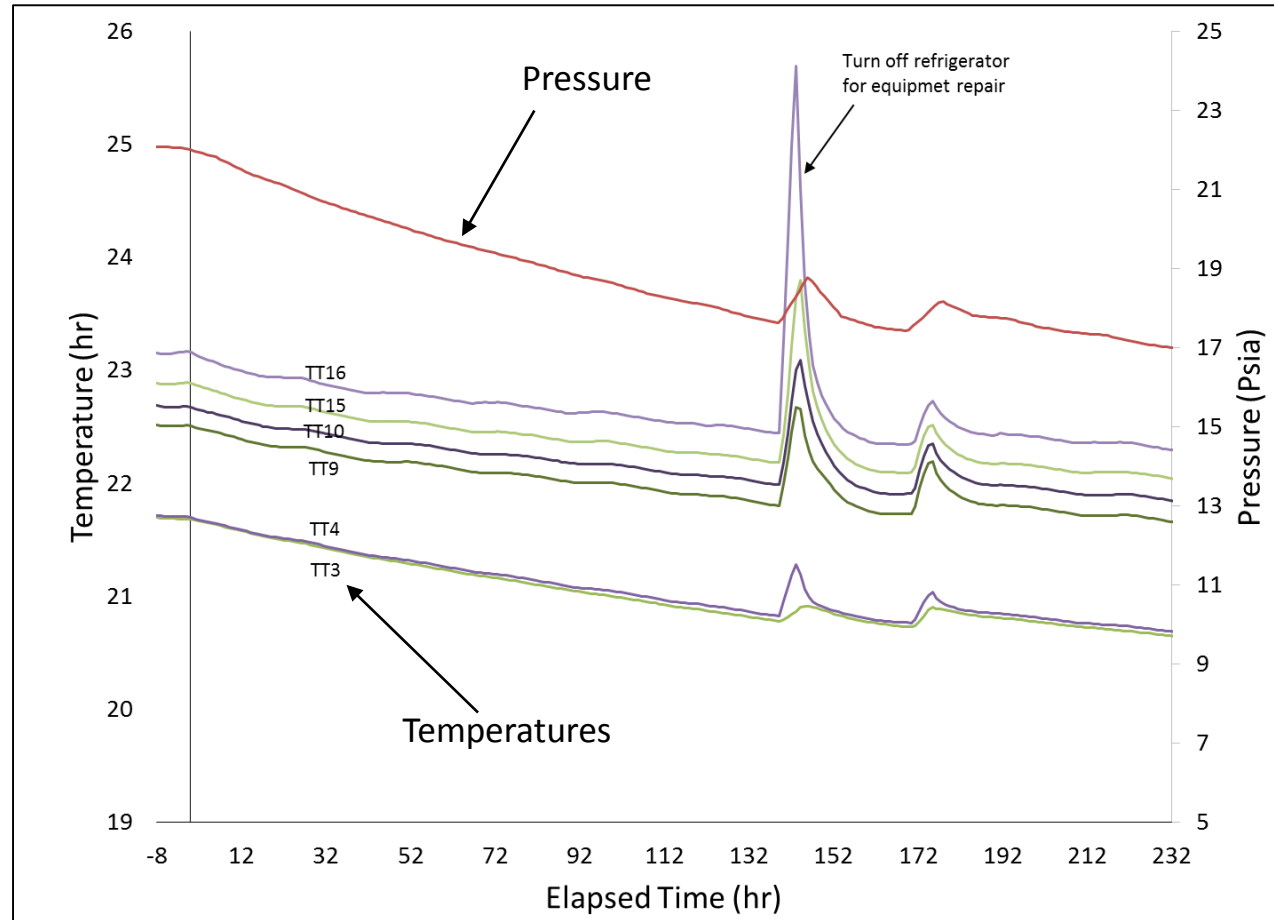
**Conclusion: IRAS using tank pressure control achieves ZBO and provides complete control over the state of the fluid**



# ZBO Temperature Control Test Results



- Linde software controlled refrigerator to achieve and maintain constant helium supply temperature.
- No  $\text{LN}_2$  pre-cooling used
- Helium supply temperature response fast and accurate
- But  $\text{LH}_2$  takes long time period to reach equilibrium state

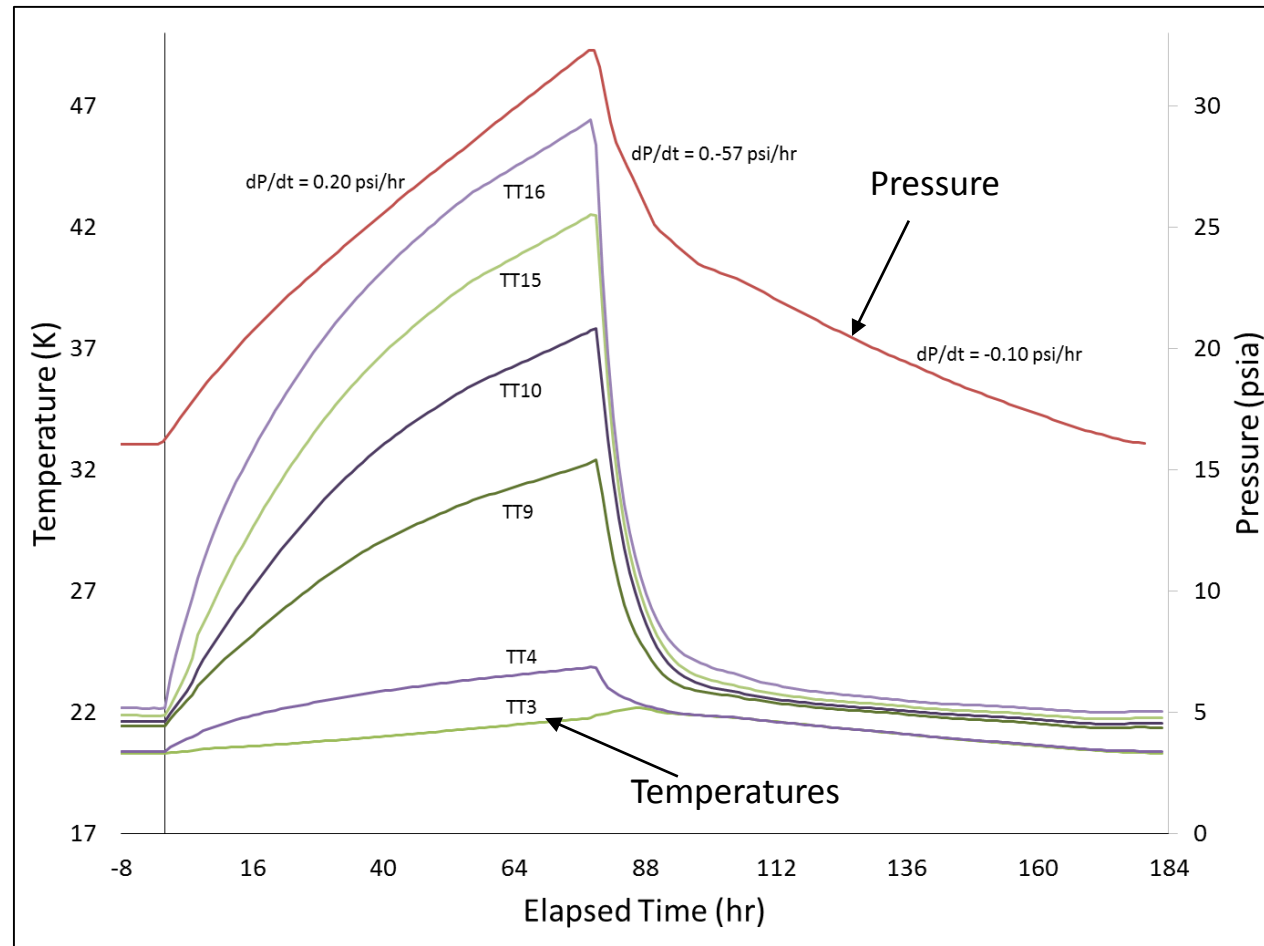


**Conclusion: IRAS using supply temperature control achieves ZBO but takes a long time to reach  $\text{LH}_2$  equilibrium state**

# ZBO Duty Cycle Test Results



- ZBO achieved in batch processes by turning on and off the refrigerator as required
- Testing was both accidental and purposeful
- Minimum electrical cost but depends on multiple start/stop cycles of cryogenic equipment
- Duty cycle varied from 1.13 (33%) to 1.16 (67%) to 3.6 (100%) on/off with no  $\text{LN}_2$  precooling

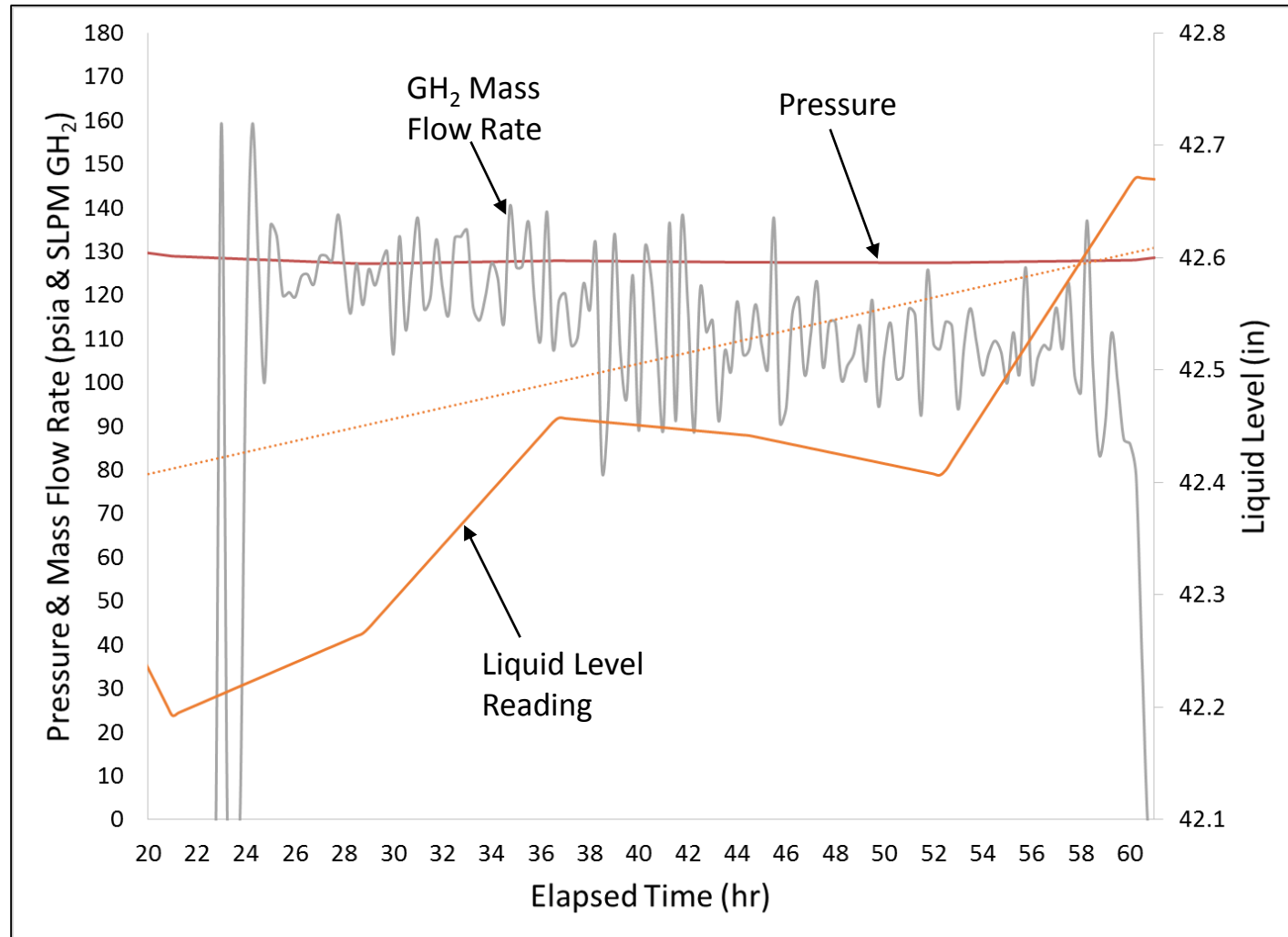


**Conclusion: IRAS using duty cycling of the refrigerator achieves ZBO with minimal energy but provides no control of  $\text{LH}_2$  state**

# Liquefaction Test Results



- $\text{GH}_2$  was controlled using a mass flow controller until the tank pressure remained constant.
- NOT optimized for liquefaction.  $\text{GH}_2$  was fed in at ambient temperature.
- Using  $\text{LN}_2$  pre-cooling, roughly 78 gal of  $\text{LH}_2$  was produced during the test.



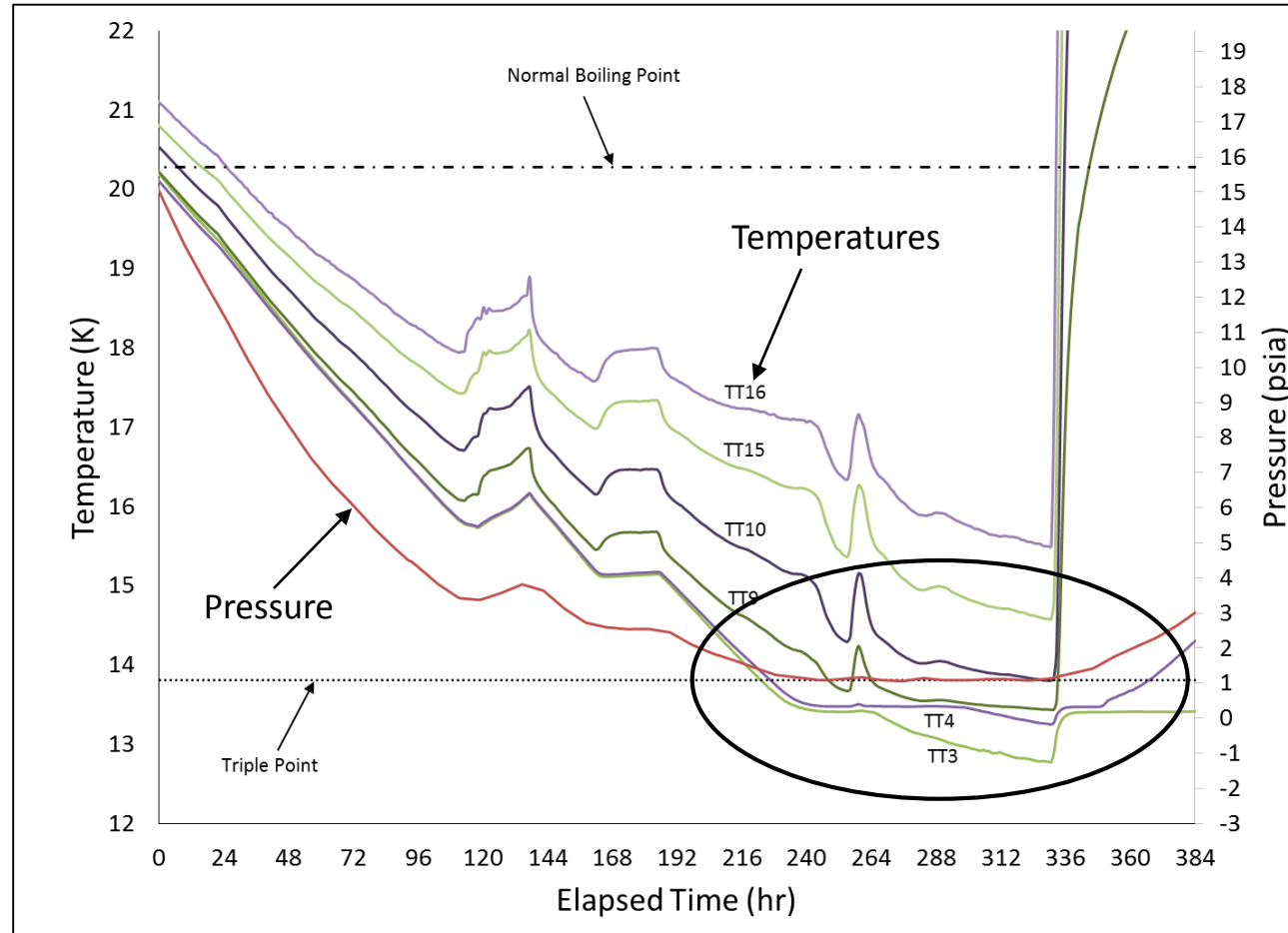
**Conclusion: Hydrogen liquefaction was achieved using IRAS, though the current system was not optimized for yield**



# Densification Test Results

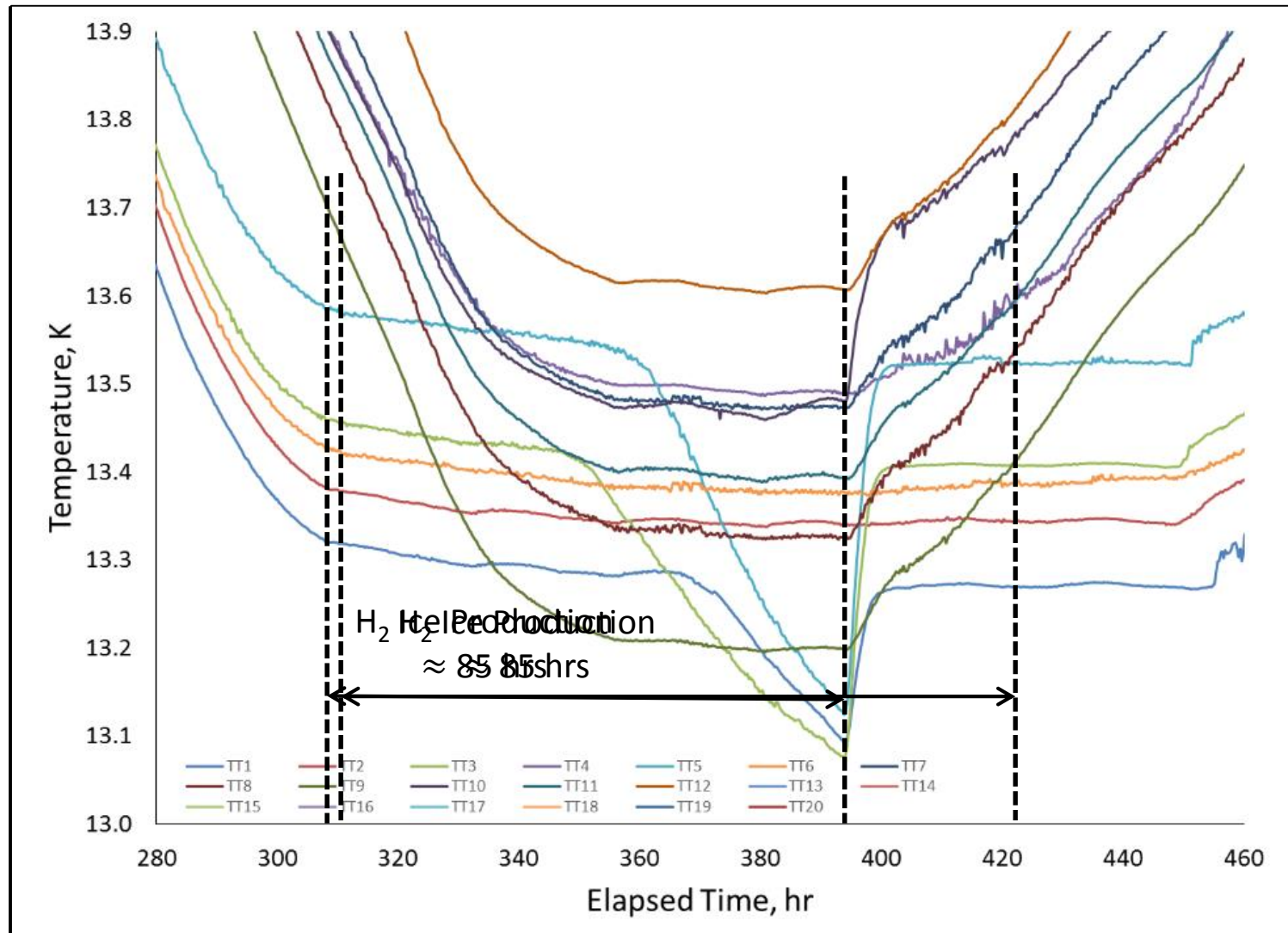


- System performance exceeded expectations!  
Min temp was expected to be  $\approx 15$  K
- Fridge ran with  $\text{LN}_2$  precooling, and densified 13,000 gallons of  $\text{LH}_2$  for 14 days.
- $\text{LH}_2$  cooled below the triple point. Minimum temp recorded was 12.6 K ( $-437^\circ\text{F}$ )
- Estimated that **3,700 lb** of hydrogen ice was formed during the course of testing; or about **5,100 gal**



**Conclusion: IRAS enables propellant densification down to the triple point**

# Slush Hydrogen Production



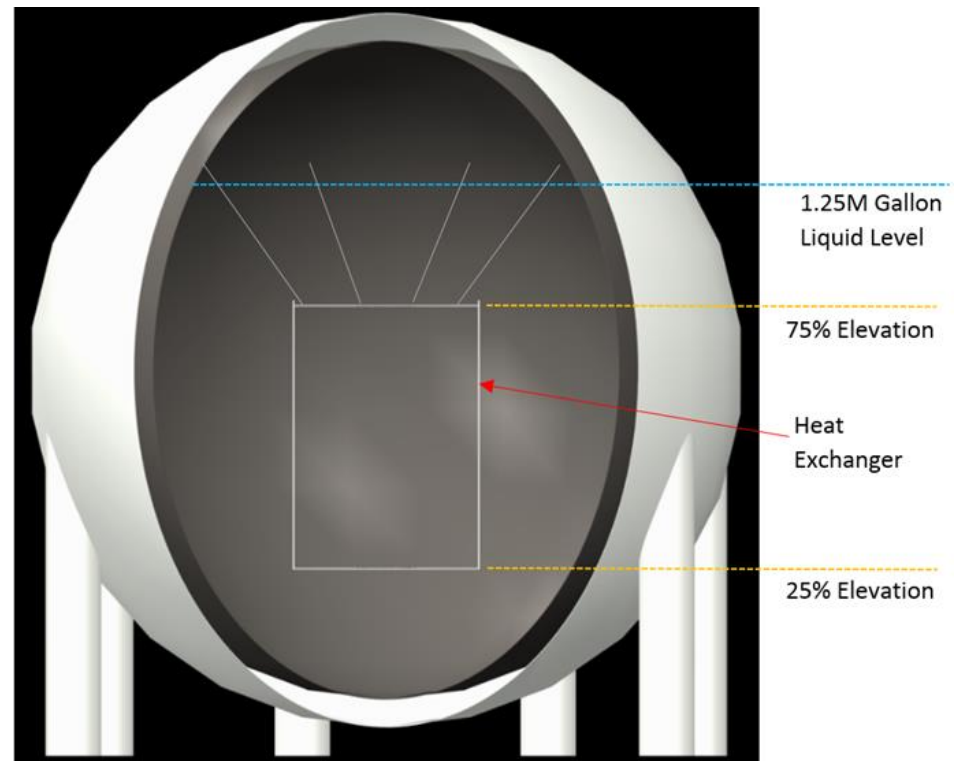
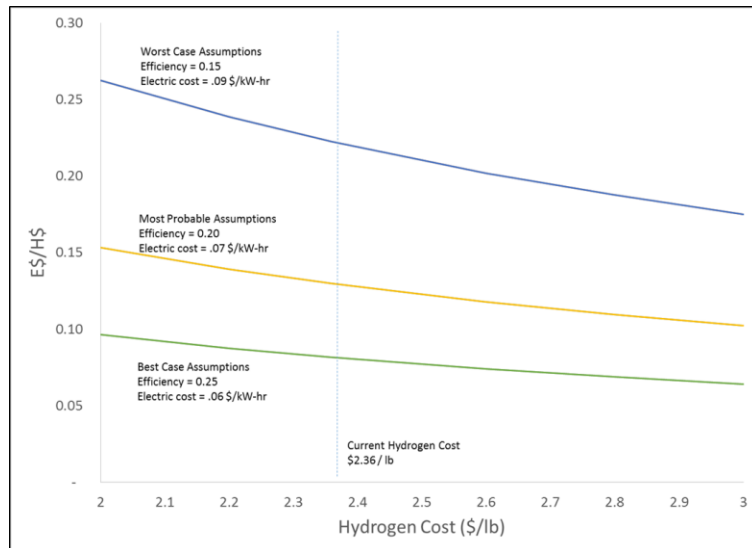
63% Tank LH<sub>2</sub> Fill Level Test

- **GODU-LH2 system has successfully met all test objectives at the 33%, 67%, and 100% tank fill level**
- **Complete control over the state of the fluid has been demonstrated using Integrated Refrigeration and Storage (IRAS).**
  - Almost any desired point along the  $H_2$  saturation curve can essentially be “dialed in” and maintained indefinitely.
- **System can also be used to produce densified hydrogen in large quantities to the triple point**
- **Exploring multiple technology infusion paths**
  - Studying implementation of IRAS technology into new  $LH_2$  sphere for EM-2 at LC39B
  - Technical interchange also occurring with STMD, LSP, ULA, DoE, KIST, Kawasaki, Shell Oil, SpaceX, US Coast Guard, and Virgin Galactic



- Proposing to GSDO to integrate the IRAS technology into a new 1.4M gallon LH2 sphere required for EM-2
  - Analysis demonstrates that \$0.15 in electricity saves \$1.00 in hydrogen
- Low risk –Failure of system just reverts back to business as usual
- Working with A&E contractor to get cost, schedule and constructability impacts

$$\frac{\$E}{\$H} = \frac{(h_{fg} + c_p \Delta T) t}{\frac{T_c}{T_h - T_c} \eta t} \frac{\text{electricity cost}}{\text{hydrogen cost}}$$



# Densified Hydrogen Flight Tank Loading Demo



- Densified Hydrogen loading of a flight weight tank was a secondary objective that was not accomplished.
- Launch Services Program and United Launch Alliance want to partner with GODU LH2 to perform densified LH2 loading demonstrations with “Cryote III” tank
- LSP will contribute modest funding and modeling support and ULA will provide Cryote III tank and supporting equipment
- Plan to submit for possible future AES funding



# Questions?

